

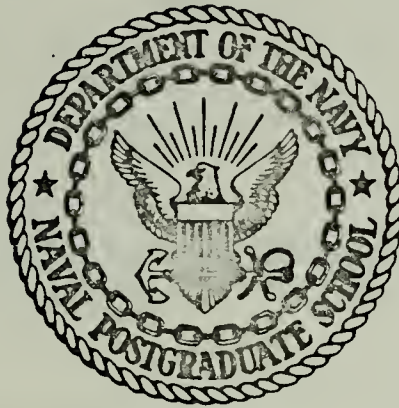
A PROPOSAL TO IMPLEMENT STATISTICAL
RELIABILITY ANALYSIS METHODOLOGY INTO THE
NAVAL AVIATION MAINTENANCE PROGRAM

Thomas Preston Driver

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THESIS

A PROPOSAL TO IMPLEMENT STATISTICAL
RELIABILITY ANALYSIS METHODOLOGY INTO THE
NAVAL AVIATION MAINTENANCE PROGRAM

by

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Herbert John Kressel

December 1974

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A Proposal to Implement Statistical Reliability
Analysis Methodology into the Naval Aviation
Maintenance Program

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Submitted in partial fulfillment of the
requirements for the degree of

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The authors' basic belief in the profit motive as an incentive for efficiency led to additional research into the decision logic employed by the commercial air carriers.

The conclusions reflect the contention that a statistical reliability based maintenance program would increase the efficiency of resource allocation and aircraft reliability. Recommendations are proposed which would aid in the implementation of such a system.

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I. INTRODUCTION

Today, in the wake of the Vietnamese conflict, the military establishment is faced with continuing reductions in available manpower and supply support resources. The reductions cannot be considered as short range difficulties which will simply "pass if waited out." The tremendous economic drain brought about by the military build-up during the Vietnamese conflict is not likely to be forgotten soon, and closer scrutiny of military efficiency is probable in the future. In addition to funding reductions, the technological sophistication incorporated into recently acquired equipment has increased the marginal cost of procurement and upkeep. The United States Navy shares this dilemma with the other military services, and while the dilemma will be felt by all commands in the Navy, this thesis is concerned with its effect on the maintenance of naval aircraft.

A result of restricted resources will be fewer aircraft purchased by the Navy at the same time that aircraft will require increasingly higher numbers of man-hours per flight-hour. A paradox is obvious since the military reduction necessarily means that fewer men will be available to perform the increased maintenance task. One thing seems certain; the Navy must seek at least the past quality levels of maintenance performance while receiving reduced levels of resources with which to do the job.

Optimal maintenance requirements and procedures give promise of providing at least a partial solution to this dilemma. Periodic maintenance policy has been lacking in analytical basis because no formal decision-making logic has existed to guide management efforts. Therefore, crucial decisions pertaining to resource allocation have tended to be based largely on tradition, experience and intuition.

A proposal for improving the inspection requirements is to implement statistical reliability analysis methodology in the Naval Aviation Maintenance Program (NAMP). This thesis has as its objective to contribute to the reduction in aircraft maintenance cost by the following:

a. To indicate how statistical reliability analysis methodology can improve the efficiency of the Naval Aviation Maintenance Program.

b. To indicate how a modified version of the commercial air carriers program can be implemented in the Naval Aviation Maintenance Program.

c. To indicate how partial implementation of a statistical reliability based system can be incorporated with minimal delay.

Unless corrective action is taken, the problem will come sharply into focus as fewer aircraft are available and additional "down time" is experienced because personnel to perform the needed task are not available.

II. RESEARCH FINDINGS

A. PRESENT PROGRAM

The determination of specific maintenance tasks to be performed and the time allowed to elapse between maintenance actions has evolved in the U. S. Navy by intuition and by an attitude of "better safe than sorry." The absence of a driving motivation, such as profit, has tended to negate innovative action which would bring about significant improvements in efficiency. The interest and the dedication of the individual managers toward their responsibilities may have been there, however, the mindset of the Naval aviation community has been one wherein preventive maintenance has occupied the highest priority in aircraft maintenance responsibilities. Too little attention has been given to the cost-effectiveness of the preventive maintenance tasks which have been required. This is particularly true of maintenance actions which required the expenditure of only time and elbow grease.

Accurate documentation of the evolution of the present aircraft maintenance program in the U. S. Navy is not available. Certain inferences can be made, however, based upon the lack of definitive policy in certain areas which have become evident as a result of this research. Demonstrative of this, are the general requirements delineated in OPNAVINST 4790.2 series and the applicable NATOPS manuals that Naval aircraft must undergo a daily preflight inspection, a plane

captain's preflight inspection, and a pilot's preflight inspection prior to the first launch of the day. Following the return from the first flight, and prior to the second, the aircraft must be postflight inspected by the flight crew, serviced and preflight inspected by the plane captain, and then preflight inspected by a pilot again. This cycle continues until the last sortie of the day, and begins anew the next day with the daily inspection. There should be a realization that the U. S. Navy neither gets nor expects to get 100% reliability as a result of these repetitive maintenance actions. Simple conditional probability computations show that in the absence of 100% reliability on every inspection, the probability of a malfunction decreases with each successive inspection without reliability ever reaching 100%.¹ The question then becomes, "At what percent reliability are maintenance managers expected to stop requiring additional preflight inspections prior to launch?" Herein lies the aforementioned omission. Realizing that 100% reliability is impossible to attain, and given the present state-of-the-art of aircraft design, what guidelines, what organizational policies, or what efficiency goals are expected of the organizational maintenance managers?

¹Reliability Factor may be computed as follows:
Reliability Factor = $P(\text{Inspector A finds discrepancy}) + P(\text{Inspector B finds discrepancy given Inspector A missed discrepancy}) + \dots + P(\text{Inspector N finds discrepancy given Inspectors A through N-1 missed discrepancy})$.

Recent efforts to improve the effectiveness of the NAMP have short-range objectives, and therefore are not providing the necessary changes in resource allocation. The most sweeping example, which applies to all aircraft models, is the concept of phased maintenance. This concept is, in reality, the old "calendar check" revised to be performed on a utilization basis rather than calendar time and split up to be required at equidistant flight-hour intervals. Implementing this program has accomplished two objectives which were published in Ref. 1. They are:

1. Reduced cannibalization, and
2. Reduced NORM time for scheduled maintenance.

The reduction in cannibalization has proved to be very effective in that it eliminates the need to "rob Peter to pay Paul," and is directly precipitated from the shorter turn-around time required for phased maintenance.

Major inspections performed in a block result in a large percentage of the total maintenance for an aircraft being performed in lengthy hangar periods, while in phased maintenance most of the work is divided into small packages which may be done during a 24-hour hangar period.

The second objective must be viewed as short-range in that it does not necessarily reflect a reduction in the Not Operationally Ready, Maintenance (NORM) time for extended periods of time. Undesirable maintenance tasks, as defined by MSG-II, are still required wherever they existed previously. The frequency of maintenance tasks under the phased

maintenance concept remains essentially unchanged from the calendar requirements; only the simultaneousness of tasks has been altered.

Due to the time constraint of this study, the feasibility of searching out all of the problem areas pertaining to each aircraft was precluded. General research into the Naval Aviation Maintenance Program has persuaded the authors that omissions and short-range objectives occur throughout the entire spectrum of Navy maintenance tasks. This may be easily demonstrated at the opposite end of the spectrum from the preflight inspections by evaluating depot level decision logic. The question is one concerning the criteria used to establish depot level maintenance intervals. One would normally expect that this information was initially gleaned from manufacturers' specifications, and that usage data was employed for subsequent periodicity. Unfortunately, this has not been the case. Depot level maintenance intervals are generally based upon "experienced judgement" more than any other input. The vendors' role has historically been one of passive agreement that overhaul at the Navy's recommended interval should not cause their product to be less satisfactory to the Navy. The "experienced judgement" demonstrated by Naval Personnel has been based on such parameters as the interval used for the previous generation's aircraft. For instance, the starting point for setting the depot level maintenance interval for the P-3 aircraft was automatically that of the P-2 even though no overhaul interval was

recommended by the vendor for commercial utilization of the P-3.

This judgement can be proved to be effective if viewed only from the perspective of ability to continue to operate aircraft over their expected service lives, and the ability to sustain an aviation safety record that has been acceptable. It has provided little, if any, insight into the problem of how much service life is forfeited or how better the safety record could have been, had it not been influenced by an infant mortality rate generated by over-maintaining the aircraft. Expenditure of consumables and human resources have been considered even less than the forfeitures in service life and safety.

Another excellent example of basing maintenance requirements for one aircraft on another may be seen by examining the proposed flying hour interval between depot level maintenance on Naval helicopters. Refer to Table 1. Note that all but two helicopters have 1000 hour intervals. The TH-57A has a 2400 hour interval and is to be inspected under a commercial contract. Other considerations, such as commercial supply support contracts, all but remove Naval discretion to deviate from this aircraft's maintenance interval. The other aircraft which deviates from the 1000 hour interval is the TH-1L, which has a 1500 hour inspection interval. Research reveals that this 50 percent increase in tour length over the UH-1L and UH-1E can easily be computed by multiplying the historical utilization by the old calendar interval and

TABLE I

HELICOPTER PDLM INTERVALS

Helicopter Model	Flying Hour Interval	Calendar Month Interval
UH-1D	1000	25
UH-1E	1000	25
AH-1G	1000	25
AH-1J	1000	25
HH-1K	1000	25
TH-1L	1500	25
UH-1L	1000	25
UH-1N	1000	25
HH-2D	1000	20
SH-2D	1000	20
SH-3A	1000	20
SH-3D	1000	20
SH-3G	1000	20
SH-3H	1000	20
CH-46	1000	20
HH-46A	1000	20
CH-53A	1000	27
CH-53D	1000	27
RH-53D	1000	27
TH-57A	2400	Commercial

THIS COMPARISON OF NAVAL HELICOPTER PDLM INTERVALS HIGHLIGHTS THE APPARENT DISCREPANCY IN THE ASSIGNMENT OF MAINTENANCE INTERVALS. WHILE THE UH-1E, UH-1L, TH-1L AND HH-1K AIRCRAFT ALL HAVE THE SAME PHASED MAINTENANCE REQUIREMENTS, SAME STRUCTURALLY OR MAINTENANCE SIGNIFICANT ITEMS, AND OPERATE IN THE SAME ENVIRONMENT, ONLY THE TH-1L HAS AN EXTENDED INTERVAL. THE SATISFACTORY OPERATION OF THE TH-1L, WITH LESS MAINTENANCE, INDICATES THAT THE OTHER MODELS ARE BEING OVERMAINTAINED. SOURCE: REF.2, P.A-4.

rounding it off to the nearest 500 hours. The glaring discrepancy in this instance is that the UH-1L's and some UH-1E's have been assigned to the aviation helicopter training command to augment the TH-1L's. The three models of aircraft all have the same maintenance significant and structurally significant items, yet the TH-1L model is allowed 50 percent more utilization than its counterpart, performing the same mission, and in the same environment. Additionally, the existing phased maintenance requirement cards, NAVAIR 01-110HCA-6-4, enumerate identical inspections for the four H-1 models presently in Naval use.

Changes to the NAMP occur frequently, but are generally examples of crisis management and seldom address the basic thought process which may have generated the crisis originally. An example of this type of program modification is the process called Aircraft Conditional Evaluation (ACE).

ACE was implemented in late 1972 and was designed to provide evidence which would justify extended intervals between Periodic Depot Level Maintenance (PDLM). The need to extend the scheduled intervals unfortunately was not the result of planned maintenance improvements, but was generated by an increasing backlog of aircraft awaiting induction into the Naval Aircraft Rework Facilities (NARF's).

The concept of ACE is straightforward since the basic idea is to prevent an aircraft from undergoing rework if its material condition is acceptable for continued safe operation. The concept, in itself, is a significant improvement

over the prior procedure of merely inducting the plane into overhaul at scheduled intervals regardless of material condition. However, the proposed flight hour sensitive program is simply the old calendar interval translated to a rounded-off aircraft utilization figure. The stopgap nature of this innovation becomes apparent under further analysis. The following scenario, which is an actual case cited in Ref. 2, (p D-1), will illustrate that nature.

Nine F-4J fighter aircraft from two Miramar-based squadrons were inspected in accordance with the ACE program in December, 1972. All aircraft had just returned from an extended deployment aboard the U. S. S. Kitty Hawk and were at, or very near to, their end-of-tour dates. Eight of the nine aircraft were recommended for and received an 18 month extension following the inspection by a NARF field team. (The inspection team spent about 300 manhours giving each plane an in-depth ACE inspection.)

Since the rework interval for the F-4J is 30 months, the intuitive reaction to the extensions should have been surprise in that following extended operations in a very demanding maritime environment, 88.9% of the aircraft inspected were deemed reliable enough to warrant a 60% extension in service life. Surprise was not the reaction, however, because those managers who were involved with this project were not simply taking a wild guess or hoping for the best; they were in fact expecting to find that at least a

significant number of the inspected aircraft could be extended, yet the PDLM interval remains the same.

ACE inspections are still held at scheduled PDLM intervals, and extensions are expected and continue to be authorized because the empirical data generated by this sampling cannot be employed in a system which is not committed to statistical reliability.

Reference 2 is a recently completed study of the Center for Naval Analyses concerning the depot level maintenance program of the Navy. The study strongly recommends the utilization of a statistical reliability based concept to replace the historical use of experienced judgement. Depot level maintenance is covered thoroughly in the study and it provides additional examples involving the A-7B and F-4B aircraft. It is mentioned here to provide the reader with direction into that area.

A general aspect of the NAMP which has become more questionable as a result of research is that which employs the continual monitoring technique. An example is the spectrographic oil analysis program. At the time of its inception, this program at least had the potential of being an effective forecasting device. No actual result data exists to back up the theoretical potential, yet the program continues. Reference 3 revealed that United Airlines abandoned a similar program because the statistical data did not confirm the reliability or economics of spectrographic analysis.

The fluid contamination analysis program, while somewhat analogous to the spectrographic process above, is different in that the contaminants do not necessarily reflect a structural breakdown. For example, hydraulic fluid can easily become discolored from carbon due to the passage of the hot fluid through a black hose. If the physical size of the particulate carbon is not sufficient to allow the filter to remove the contamination and the particulate matter is injurious to the hydraulic system, then continuous monitoring and changing of the fluid is probably not the best answer. It would seem intuitive to incorporate a more efficient filter or remove the source of the carbon rather than to continue to expend resources indefinitely. On the other hand, if analysis shows that the contamination is not injurious to the hydraulic system, further maintenance action is simply not desired.

Another requirement, less important from a cost standpoint but which is indicative of inefficient allocation of manpower, is the recording of counting accelerometer readings installed in high performance aircraft. Reference 4 (p. 12) revealed that nearly 70 percent of the accelerometers were found to be in need of calibration or repair, or both, during periodic checks. If the data being collected is that unreliable, then obviously it provides a poor basis for scheduling additional maintenance actions.

B. STATISTICAL RELIABILITY ANALYSIS

To fully understand the ~~concept~~ of the statistical reliability based maintenance program, certain properties of reliability must be recognized. One of the most basic characteristics is the effect of time upon reliability. To insure that the reader is cognizant of the various aspects of this phenomenon, a brief discussion of the age-reliability relationship follows.

It is generally accepted that all mechanical devices deteriorate with age. As an aircraft component ages, the probability of failure increases. The increase continues until a point is reached where a 100 percent failure probability exists. As intuitive as this may seem, failure to recognize the relevance of how reliability changes with age and when it changes is a critical omission in the thinking of many managers.

The time-based bathtub curve, Figure 1, from Ref. 5 (p. 5.4.4), has almost universal applicability to the analysis of age vis-a-vis reliability. Early in the operating life of a component, in the period known as break-in or burn-in, there is a time during which the probability of failure is very high. This is the area of infant mortality, region I. The high failure rate may be caused by several factors, such as inherent material defect, design deficiency, or improper maintenance.

The next consecutive area, region II, is a relatively long period of time with a nearly constant probability

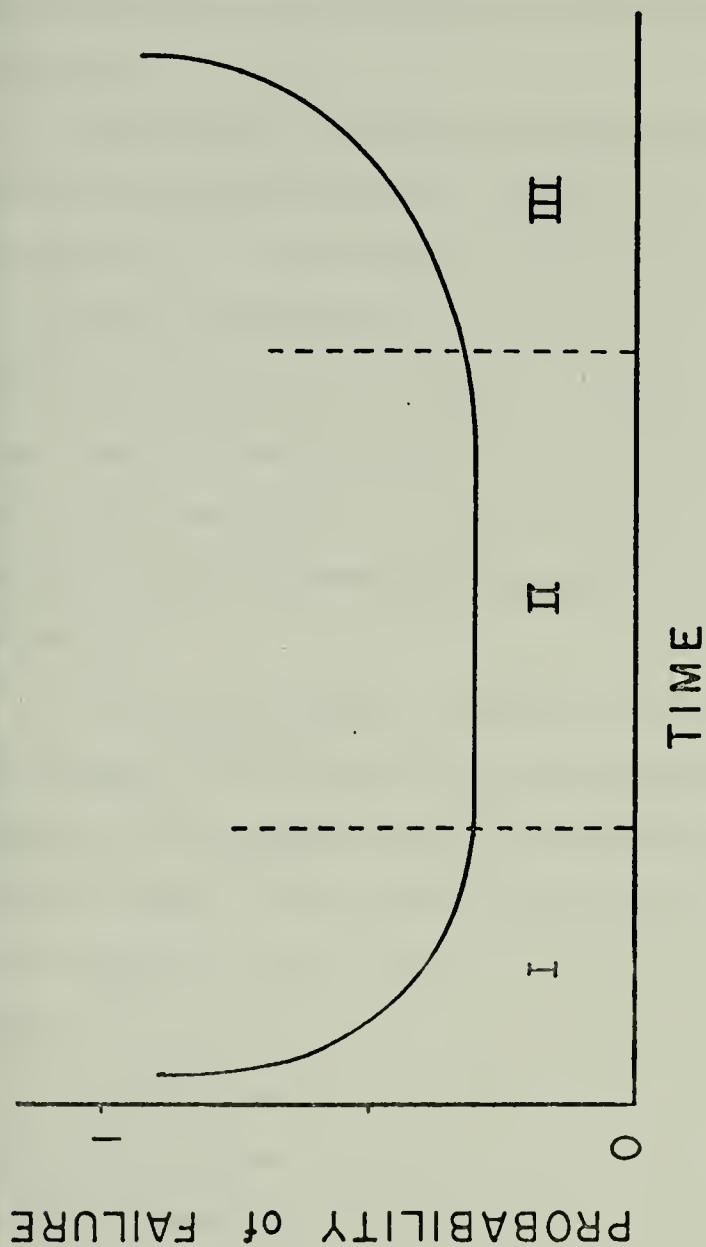


FIGURE 1
AGE VERSUS RELIABILITY

THE BATHTUB CURVE IS A CONDITIONAL PROBABILITY OF FAILURE CURVE OR A HAZARD FUNCTION. THE INITIALLY HIGH COMPONENT FAILURE RATE OF REGION I WHICH RAPIDLY DECREASES TO THE STEADY STATE VALUE IS REFERRED TO AS INFANT MORTALITY. REGION II IS A LONG PERIOD OF SATISFACTORY OPERATION WHEREIN NO EQUIPMENT MAINTENANCE NEED BE PERFORMED. THE UPSWEEP OF REGION III REPRESENTS WEAROUT DUE TO AGE. SOURCE: REF. 5, P.5.4.4.

of failure. It is this long period of high reliability and satisfactory operation which represents the productive life of the component. The final portion of the curve, region III, is one of rapidly increasing probability of failure.

The reality of aircraft maintenance is that all aircraft components progress through the three regions depicted in Figure 1. Realization of the implications of this graph are absolutely essential to the planning of a logical, efficient maintenance program. Keeping in mind that the time span for each region and the respective slopes of the curve will vary with various aircraft components, three categorical statements may be made of age-reliability effects:

1. If one removes, replaces, or performs scheduled maintenance on an item which is operating satisfactorily in region I, the result will be a decrease in the reliability of that item. This is true because the new or recently maintained part must begin the infant mortality stage over again, at a point higher on the probability of failure curve.

2. If a satisfactorily operating part is removed, replaced or given scheduled maintenance in region II, there will be a reduction in reliability, for the same reason as stated in (1) above. The replacement or maintenance process, therefore, is at best worthless and may even be injurious to further reliability.

3. If the component exhibits the behavior of region III early enough in its service life, so that large numbers of these components survive to that time, then--and only then--can it be rational to remove, replace, or perform scheduled maintenance on that item.

In the early 1960's, commercial air carriers found that they owned and operated aircraft which were becoming prohibitively expensive to maintain. The problem of increasing maintenance costs became even more significant with the development by Boeing Aircraft Corporation of the B-747. The sheer economics of holding a large expensive airplane on the ground for routine maintenance work caused the airline maintenance managers to develop a maintenance program based not only on dependable quality, but also on the effective use of resources. The outgrowth of the efforts of the commercial air carriers was a maintenance program planning document called MSG-I. When MSG-I was completed in 1968, it was the first statistical reliability analysis (SRA) concept to provide a decision logic which could determine what maintenance was to be performed and at what intervals it would be accomplished.

The success of the program and the advent of additional wide-bodied jet airliners created the need for a more general maintenance planning scheme. MSG-I was then refined, through the joint efforts of the commercial air carriers and the Air Transport Association, into a program applicable to all aircraft and was based upon the following presuppositions:

Maintenance tasks are desirable only if:

1. Failure of a component adversely affects operating safety, or
2. It is more economical to replace or repair that part prior to failure than at failure, and
3. Statement 1 or 2 is true and the item has an adverse age-reliability relationship.

The refined logic, designated MSG-II and outlined in Ref. 6 is an SRA concept and is very effective and highly productive for the airline companies.

The problems encountered by the commercial carriers in the area of economy of maintenance are becoming more applicable to the operations of the U. S. Navy as available labor and consumable resources become less plentiful. Efforts to improve the efficiency as well as the quality of aircraft maintenance in the U. S. Navy are well-documented in numerous studies and directives. These efforts include preparation to implement the MSG-II concept into the Naval Aviation Maintenance Program as will be discussed in the next section of this paper.

C. MSG-II

As the commercial air carriers focused their attention on the need to improve the economic efficiency of their maintenance programs, the phenomena illustrated in Figure 1 became increasingly important, i. e., if scheduled maintenance actions were occurring within the first half of region II,

then manhours and supply support were at least twice as expensive as necessary. Proportional savings could be attained by statistically computing the optimum intervals and by adjusting scheduled maintenance tasks accordingly.

Another realization to evolve from this type of analysis was the effect of scheduled maintenance actions on items which did not demonstrate an adverse age-reliability relationship. An investigation of components which demonstrate a random failure rate as compared to those which experience failure as a function of age was made by representatives of the air carriers and manufacturers while developing the MSG-II concept. The findings of this group were reported in Ref. 6 (para. 2.3.12) as follows:

It has been found that overall measures of reliability of complex components, such as the premature removal rate, usually are not functions of the age of these components . . . In this event, scheduled overhaul cannot improve the operating reliability. Engineering action (redesign) is the only means of improving reliability. These components should be operated, therefore, without scheduled overhaul. Note: Systems or items which require no scheduled task are included in condition monitoring.

Some items do, however, show very definite relationships between age and reliability. Analysis of these items show that resistance to failure decreases with age although the stress applied to the equipment remains approximately evenly distributed throughout the expected life-cycle of the component. A pictorial description of the resistance/stress/age relationship is provided in Figure 2 which was extracted from Ref. 7 (p. 12). It should be recognized that Figure 2 represents the graphic inverse of stages II and III of

Figure 1. (The authors reiterate that the slope of the resistance curve is a function of the individual component being analyzed and is shown here for visual demonstration only.)

The purpose of the airline/manufacturers' maintenance planning document is to maintain the inherent design level of operating safety. The key word in this phrase is inherent. There is NO maintenance action which will increase operating safety beyond that which the design itself affords. Implicit in this stated purpose is the maintenance of those levels as efficiently as possible, and is manifested in the abolition of maintenance tasks which neither improve the reliability of items whose failure would adversely affect operating safety nor are more economical to replace prior to failure.

The MSG-II decision logic is based upon the identification of all items judged by the manufacturer to be most important from a safety or economic standpoint, their modes of failure, and their probability of failure. Once the identification process has been accomplished, a list of maintenance tasks which could restore the original reliability is enumerated. After determining what can be done, the next logical step is to determine what must be done to preclude failure which would adversely affect operational safety. The final determination concerns what maintenance actions should be accomplished for economic reasons, e. g., actual failure could result in damage to other components and/or significantly more expense in the repair of the failed item.

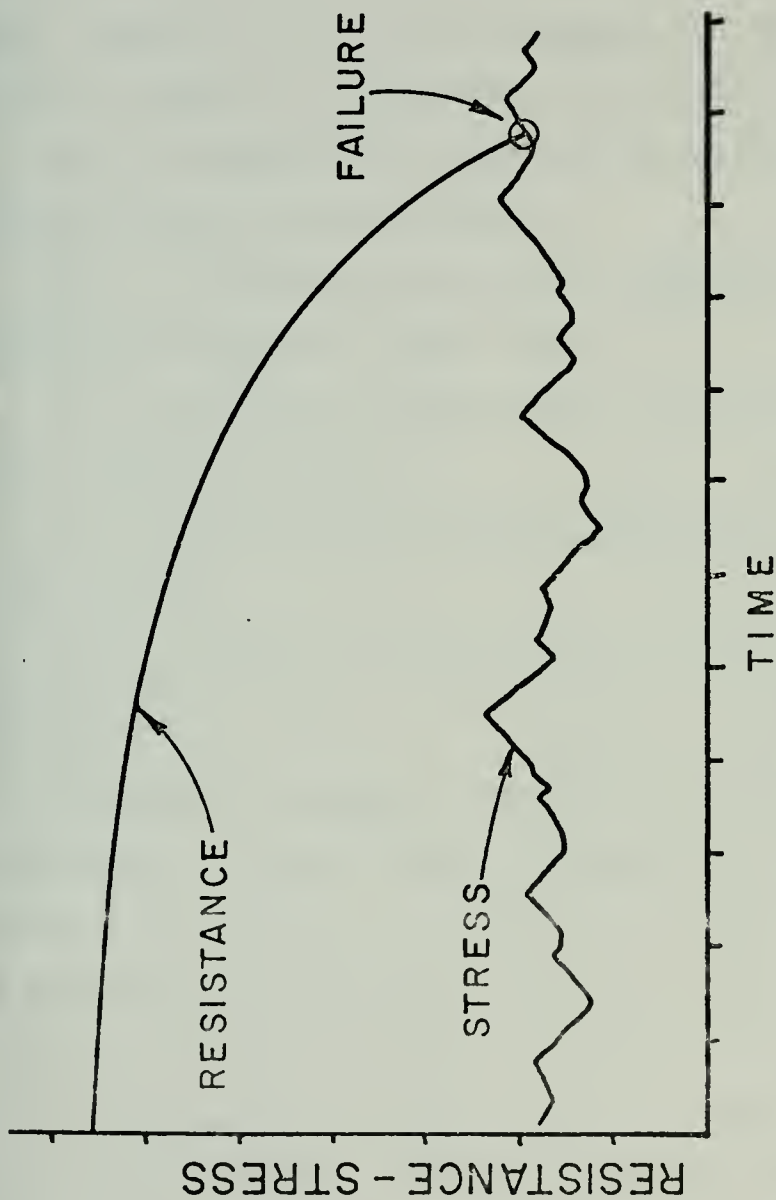


FIGURE 2

MODEL OF FAILURE MECHANISM

THIS GRAPH DEPICTS THE DECREASE OF FAILURE RESISTANCE WITH AGE AND THE RESULTING FAILURE WHICH OCCURS AT THE INTERSECTION WHERE RESISTANCE EQUALS APPLIED STRESS. THIS EXAMPLE IS APPLICABLE TO SIMPLE DEVICES ONLY OR TO A SPECIFIC FAILURE MODE OF A SOPHISTICATED DEVICE.
SOURCE: REF.7, P.12

Figure 3 provides a diagrammatical view of the decision tree suggested by the MSG-II for system and component analysis. Five questions must be answered for each component analyzed. Questions (a), (b) and (c) must be answered for each failure mode, question (d) for each function and question (e) for the item as a whole. The questions are listed below:

(a) Is reduction in failure resistance detectable by routine flight crew monitoring?

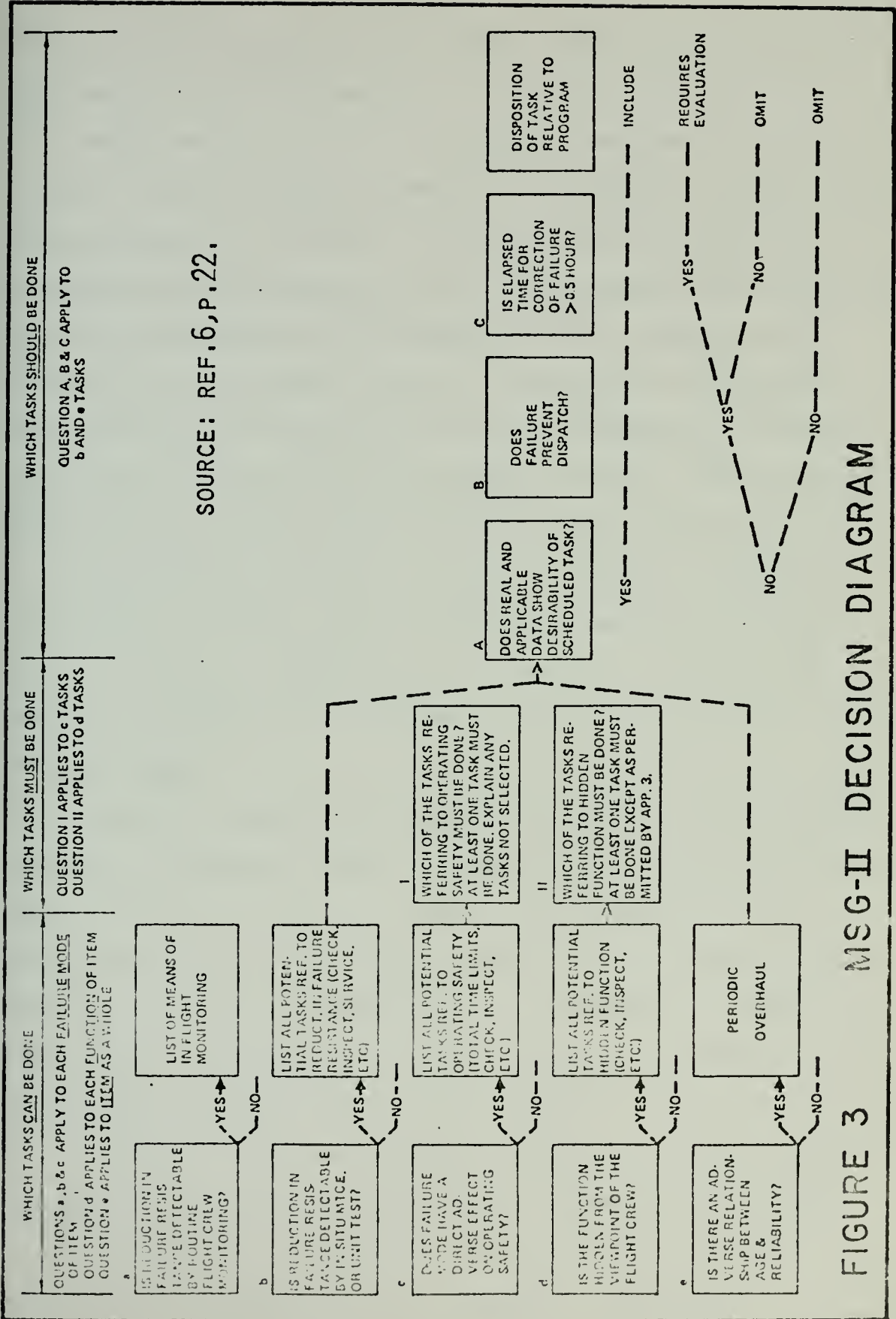
(b) Is reduction in failure resistance detectable by in situ maintenance or unit test?

(c) Does failure mode have a direct adverse effect upon operations safety?

(d) Is the function hidden from the viewpoint of the flight crew?

(e) Is there an adverse relationship between age and reliability?

Reliability analysis enters into all three types of maintenance in use in MSG-II: hard-time, on-condition, and condition monitoring. The latter two types allow the reduction of preventive maintenance by repairing most parts only when failure or incipient failure is detected. If the failure rate or unscheduled removal rate of a particular component exceeds an allowable level, a corrective engineering change can be initiated. Repeat component failures, which keep recurring after apparent repairs have been made, can be identified as soon as possible so that the true cause of the



failure can be diagnosed and further costly and unnecessary maintenance may be prevented.

Hard-time control and on-condition maintenance have in the past been the usual procedures for keeping critical items in satisfactory condition. Hard-time control requires that a component be overhauled after a preset usage period regardless of the item's condition and assumes that an adverse age-reliability relationship exists. Reliability analysis has shown that this is not the case for the majority of aircraft components and that hard-time removals result in the unnecessary maintenance of many perfectly functioning aircraft parts.

On-condition maintenance requires tests of components at regular intervals. These checks are made with the item either removed or installed on the aircraft. If the item meets all performance standards it remains in operation until the next test.

Condition monitoring became practical with the numerous redundant systems of modern aircraft which allow many critical components to remain in operation until deterioration becomes detectable. Statistical analysis of the performance data of the items and systems must be performed to anticipate degradation and remove the part in question or alter the maintenance program of that item itself.

The three aspect maintenance system facilitates trend analysis of failures thereby making it easier to plan and control maintenance resources. Resources are allocated assuming a particular level of component reliability.

If the removal rate either increases or decreases substantially, the impact on the aircraft maintenance facilities will require reallocation of these resources.

The results attained by the commercial air carriers' implementation of a statistical reliability concept are very impressive. Reference 7 (p. 7) lists some of these important results, two of which are:

. . . we now have a logical process for designing safe, effective maintenance programs for transport airplanes--even though they may not yet have been flown . . . Some insight of the value of this process can be seen from the fact that while the initial maintenance program for the DC-8 specified time-limited overhauls for about 300 units, the initial program for the 747 and DC-10 specified less than 10 items. The in-service reliability of the 747, the first airplane having its maintenance program determined wholly by the decision tree process I have described (MSG-II) is powerful evidence of the validity of this innovative technique . . .

. . . we have eliminated the requirement for time-limited overhaul for jet engines . . .

Reference 2 (p. 42) shows that the cost of operating a Boeing 707 decreased by \$6.05 per flight hour between 1963 and 1971. This reduction is measured in current dollars and occurred despite rising labor and material costs. This cost decline is especially significant when multiplied by the thousands of 707 flight hours flown by the major airlines each year. During the same period, the accident and fatality rates also declined.

Table 2, from Ref. 2 (p. 43), shows the percent of airliner components in the various maintenance classes and

TABLE 2

PERCENT OF ~~AIRLINER~~ COMPONENTS
IN THE VARIOUS
MAINTENANCE CLASSES

	HARD TIME		ON CONDITION or COND. MONITOR	
	Original	Current	Original	Current
707/720	99	40	1	60
727	55.5	40	44.5	60
737	53	29	47	71
747	--	0.3	--	99.7
DC-10	--	2	--	98
L-1011	--	2	--	98

THIS TABLE SHOWS THE RESULTS OF A RIGOROUS AND RETROACTIVE APPLICATION OF RELIABILITY CONCEPTS TO MODERN JET AIRLINERS. THE REDUCTION IN HARD TIME COMPONENTS HAS THE RESULT OF GREATLY IMPROVING OPERATIONAL READINESS WHILE EXTENSIVELY REDUCING MAINTENANCE TIME AND LABOR COST.
SOURCE: REF. 2, P. 43.

contrasts the original percentages on those aircraft which were placed on the MSG-II concept retroactively.

It becomes quite evident from Table 2 that the airlines were overmaintaining their aircraft originally, but have been able to greatly improve their resource allocation by incorporating the MSG-II decision logic. Hard time items have decreased tremendously while on-condition and condition monitored items have increased.

D. TACIT ACCEPTANCE OF MSG-II

The Department of Defense has been the recipient of mounting pressure from the General Accounting Office (GAO) to eliminate wasteful or inefficient practices. Emanating from these efforts by the GAO have been numerous revisions to the NAMP, some of which employ the techniques of statistical reliability analysis.

The most advanced application of SRA in the NAMP is in the P-3 community where the Improved Maintenance Program (IMP) is the operational reality of a contract between the U. S. Navy and Lockheed Aircraft Corporation, manufacturer of the P-3 aircraft, wherein Lockheed designed an SRA based maintenance program for the P-3. The consulting services of the Director of Maintenance Analysis of United Airlines was secured to direct and/or assist in the formulation of the program.

Reference 8, in August 1973, tasked Patrol Squadron 40 to initiate IMP and to determine its applicability to the

Navy's operating environment. Periodic progress reports were submitted to the Commander of Patrol Wings, Pacific Fleet. Based upon the results of the evaluation as recorded in the progress reports, Ref. 9 provided authority for Patrol Squadron 40 to continue under the IMP indefinitely. All P-3 squadrons in the Pacific Fleet are now operating under the IMP.

The results of the evaluation performed by Patrol Squadron 40 are available in toto in References 1, 10, 11, 12 and 13. Tables 3 and 4, based on 13 months' data, provide a very impressive example of the improvements in efficiency and savings made possible by a complete SRA aircraft maintenance plan.

In addition to the IMP in use among the Pacific Fleet patrol squadrons, a contract has been awarded to United Airlines to develop a depot level maintenance program for the F-4J fighter aircraft. Concurrently, Lockheed Aircraft Corporation has been tasked to produce an SRA based organizational level program for the S-3A while NARF Alameda has been given the assignment to develop a similar program for the depot level inspection of the same aircraft. The lack of definitive direction in the total maintenance effort is obviated by the omission of an organizational SRA program for the F-4 aircraft.

In view of the enthusiasm and support given to the program utilized by the P-3 commands and the overt efforts of

TABLE 3

SCHEDULED MAINTENANCE - ISOCHRONIC VS. IMP

CALENDAR MAINTENANCE

Average Down-time for 18
Calendar Inspections 15 days/Inspection

2 Calendar Insp/year X
15.3 days/Inspection 30 days/Acft/year

IMPROVED MAINTENANCE PROGRAM

Average Down-time for 46
Phase Inspections 1.7 days/Phase

4 Phases/year X 1.7
days/Phase 6.8 days/Acft/year

SAVINGS

In days/Acft/year 23.8

In percentage 77.8 %

THIS TABLE COMPARES THE AVERAGE OUT-OF-SERVICE TIMES FOR P-3 AIRCRAFT IN THE IMPROVED MAINTENANCE PROGRAM (IMP) AS OPPOSED TO THE PREVIOUS CALENDAR METHOD OF AIRCRAFT INSPECTIONS. THE PERCENTAGE SAVINGS OF THE IMP DEMONSTRATE A DISTINCT ADVANTAGE OVER THE ISOCHRONIC METHOD AFTER ONLY 15 MONTHS' USE.

SOURCE: REF. 1, P. 2 OF ENCLOSURE 1

TABLE 4

SCHEDULED MAINTENANCE- ISOCHRONIC VS. IMP

CALENDAR MAINTENANCE

Average Maintenance Man- hours/Calendar Inspection	354.8 MH/Inspection
---	---------------------

2 Calendar Insp/year X 9 Aircraft X 354.8 MH/Insp	6395.4 MH/year
--	----------------

IMPROVED MAINTENANCE PROGRAM

Average Maintenance Man- hours/Phase Inspection	115.8 MH/Phase
--	----------------

4 Phases/year X 9 Aircraft X 115.8 MH/Phase	4268.8 MH/year
--	----------------

SAVINGS

In Man-hours/year	2126.6
-------------------	--------

In percentage	49.9 %
---------------	--------

THIS TABLE COMPARES THE LABOR ASPECTS OF A TIME-PHASED SCHEDULED MAINTENANCE PLAN (IMP) VERSUS THOSE OF THE PREVIOUS CALENDAR SYSTEM. THIS DATA REPRESENTS ONLY 15 MONTHS' UTILIZATION OF THE IMP BUT ALREADY ILLUSTRATES ITS EFFECTIVENESS IN REDUCING THE MANPOWER REQUIREMENTS OF A P-5 AIRCRAFT SQUADRON.
SOURCE: REF. 1, (P.1 OF ENCLOSURE 1)

the Naval Air Systems Command to broaden the application of SRA to other aircraft, at least tacit approval of the concepts and techniques of the MSG-II by the managers of the NAMP is obvious.

E. SUMMARY

The decision process utilized by the U. S. Navy concerning aircraft maintenance tasks has been satisfactory in the past, perhaps because manpower has been abundant and Congressional appropriations have been relatively high.

The inadequacies of the present system cannot continue to be tolerated now that improved managerial techniques are available and recognized. More maintenance requirements are not necessarily better, and historical procedures have not necessarily generated the proper data with which to forecast maintenance requirements for new equipment. The decision logic of the MSG-II enables Navy maintenance managers to replace much of the subjective evaluation extant in the present system with quantifiable judgement based upon the empirical data available through statistical reliability analysis.

Reference 9 authorized indefinite continuation of the Improved Maintenance Program in the Pacific Fleet patrol community, and occasional attempts have subsequently been initiated in other communities in a random manner. The lack of top level commitment to an overall concentrated effort to incorporate the improved methodology has resulted in a

slow transition to SRA and is costing the Navy in excess of \$300 million annually.

The Enlisted Requirements Plan of 1 October 1974 shows an allowance for 62,074 Group IX (Aviation) ratings. (The figure excludes non-maintenance Air Controlmen, Aerographers, Photo Intelligence Technicians, and non-rated strikers.)

Using the Naval Air Systems Command estimating figure from Ref. 14 of \$10.00 cost per maintenance man-hour X 8 hours per day X 5 days per week X 48 weeks per year X 62,074 maintenance personnel, the total cost for aviation maintenance labor is \$1,191,820,800 per annum. A 26 percent savings in labor cost would exceed the estimated \$300 million--and the only community fully utilizing the SRA concept reported a 36 percent savings the first year!

As cutbacks in Congressional funding and manning levels have already demonstrated, improved managerial techniques and procedures to reduce waste and inefficiency are absolutely essential if Naval commitments of the future are to be met. Concern for the efficient employment of available maintenance resources must become more prevalent at all levels of planning and operations. Existing maintenance practices and decision logic must be re-evaluated to ascertain their applicability to the imminent austerity faced by the U. S. Navy.

The potential for conserving resources resulting from implementation of an SRA concept is present at every level of maintenance supervision within the Navy, and therefore impossible to enumerate in this study. It is possible

however, to direct the reader's attention to several of the more obvious savings which by themselves are convincing enough to warrant adoption of statistical reliability analysis techniques. They are:

1. Since the total number of aircraft procured includes some percentage of overbuy to maintain the necessary complement while some are undergoing Periodic Depot Level Maintenance (PDLM), longer service tours based upon empirical data generated by SRA would indicate a corresponding decrease in the overbuy percentage. This overbuy is addressed in the study by the Center of Naval Analyses (Ref. 2, p. F-7), and is assigned a value of approximately 15 percent.

Obviously, all overbuy requirements cannot be eliminated. However, every source researched for this paper states that periodic depot level maintenance is performed too frequently. Reference 15 (p. 11), in discussing the F-4 aircraft, states " . . . the data that we analyzed suggest that the current 24 month full IRAN (U. S. A. F. equivalent of PDLM) interval can be conservatively extended up to 48 months." Reference 1 (p. 2), shows a 79.1 percent reduction in downtime resulting from the incorporation of an SRA. The crux of the above discussion is that by utilizing modern management techniques in the F-14 procurement program, the U. S. Navy could realize at least a savings of 50 percent of the overbuy cost associated with the F-14. If that figure is introduced into the F-14 program to estimate

possible savings in initial procurement, the computations of table 5 result.

2. By continuing components in service until failure (on condition maintenance) fewer consumables such as filters, O-rings, nuts and bolts, etc. would be required for any scheduled maintenance. Even a 25 percent savings, which is a highly conservative estimate of the potential of this program, could easily exceed 1 percent of the aircraft maintenance budget, or about \$10 million annually.

3. This paper is primarily directed at man-hour savings. Probable savings can be expected to exceed 35 percent of the current anticipated maintenance effort, and simultaneously maintain existing safety standards--if not exceed them. Reference 1 (p. 1 of enclosure 1), shows that Patrol Squadron 40 experienced a 36 percent reduction in required man-hours during the first year after shifting to the SRA maintenance program. This reduction represents a \$2.255 million annual savings by the P-3 community alone.

The decision logic provided by the statistical reliability analysis of the MSG-II does not constitute a panacea for the problems of resource allocation. It does supply a much needed and much improved methodology with which to attain the efficiency goals of an organization while improving the quality of the final output.

TABLE 5

SAVINGS IN F-14 PROCUREMENT THROUGH REDUCTION IN INITIAL PROCUREMENT

TOTAL AIRCRAFT PURCHASE	334 Aircraft
COST - Airframes plus spares	\$4.86 Billion
OVERBUY FACTOR	15 %

COST PER AIRCRAFT

$$\text{\$4.86B} \div 334 = \text{\$14.55 Million}$$

QUANTITY OF OVERBUY

$$334 \times 15 \% = 50.1 \text{ Aircraft}$$

COST OF OVERBUY

$$50.1 \times \text{\$14.55M} = \text{\$728.96 Million}$$

SAVINGS

$$50 \% \times \text{\$728.96M} = \text{\$364.48 Million}$$

THIS TABLE ILLUSTRATES THE POSSIBLE SAVINGS FROM STATISTICAL RELIABILITY ANALYSES PRIOR TO INITIAL AIRCRAFT PROCUREMENT. SINCE FEWER AIRCRAFT ARE OUT OF SERVICE FOR DEPOT MAINTENANCE, FEWER AIRCRAFT ARE REQUIRED TO SUPPORT COMBAT READINESS. SOURCE: REF. 2, P.F-7 AND REF. 16.

III. CONCLUSIONS AND RECOMMENDATIONS

No prudent manager and certainly not the authors of this paper desire to lower the probability of safe flight. Conversely, the intent is to improve safety wherever possible, but to simultaneously remove the guise of safety which is frequently used to prevent innovation and explain away inefficiency. Critical analysis of the Naval Aviation Maintenance Program must be accomplished if efficient planning is to be obtained. The authors define efficient planning as reducing (wherever possible) the required flight operations in Region I of Figure 1, the infant mortality range, and increasing the opportunity of operations in Region II, the time of nearly constant resistance to failure. This can be accomplished by avoiding overmaintenance through the application of empirical data which presently is available or can be obtained. Figure 4 represents an effective periodic maintenance program when the maintenance action is taken at some point where the probability of catastrophic failure has become unacceptable . . . then and only then is maintenance action desirable.

In order to achieve more efficient management in the Navy maintenance program the following conclusions and recommendations are submitted:

1. Conclusion. The Navy is presently operating its aircraft maintenance program inefficiently and the expertise

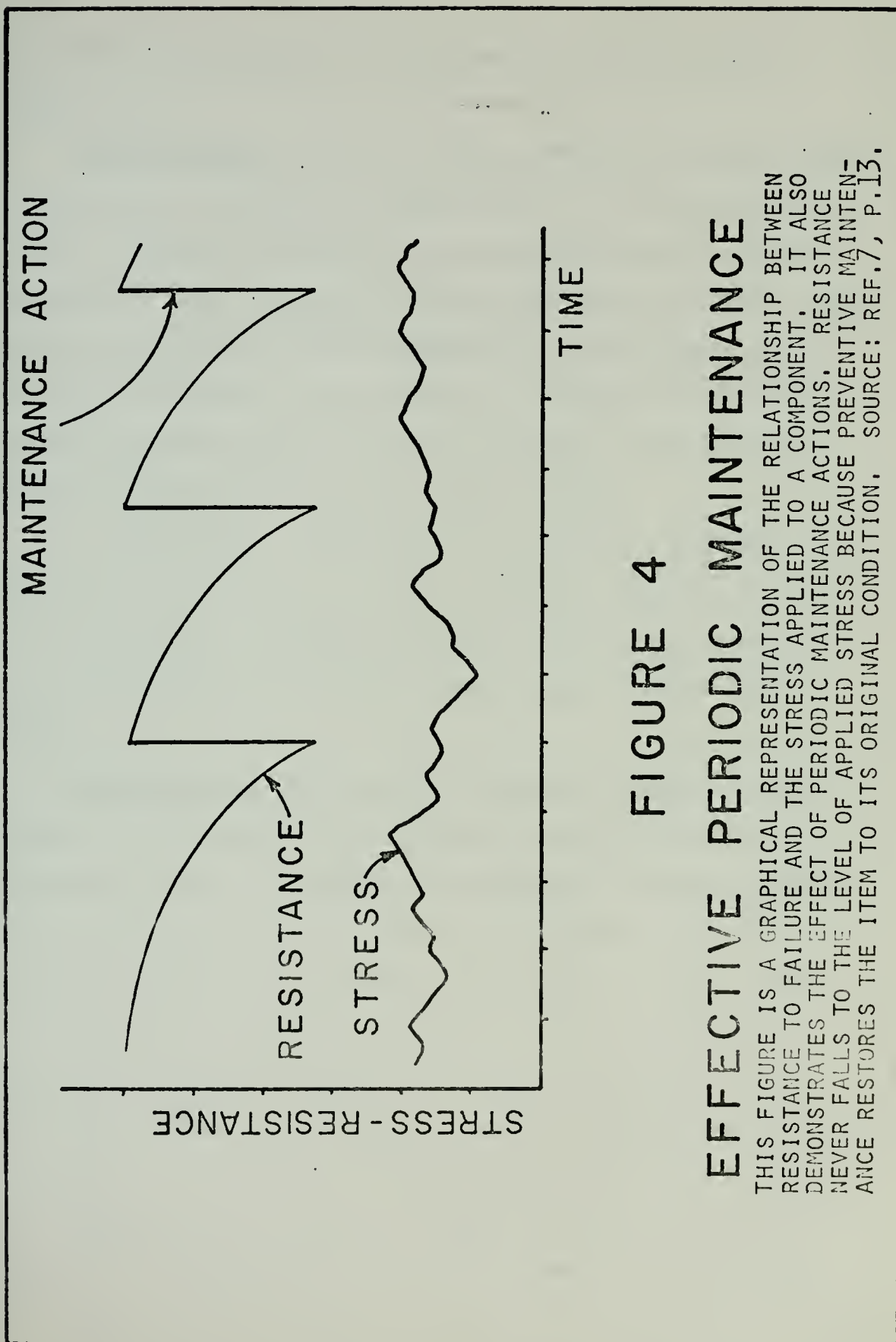


FIGURE 4
EFFECTIVE PERIODIC MAINTENANCE

THIS FIGURE IS A GRAPHICAL REPRESENTATION OF THE RELATIONSHIP BETWEEN RESISTANCE TO FAILURE AND THE STRESS APPLIED TO A COMPONENT. IT ALSO DEMONSTRATES THE EFFECT OF PERIODIC MAINTENANCE ACTIONS. RESISTANCE NEVER FALLS TO THE LEVEL OF APPLIED STRESS BECAUSE PREVENTIVE MAINTENANCE RESTORES THE ITEM TO ITS ORIGINAL CONDITION. SOURCE: REF.7, P.13.

to rectify the situation is available within the Naval organization.

Recommendation. The U. S. Navy should officially adopt a statistical reliability based system for all types of aircraft to establish maintenance requirements and intervals. Adoption of such a program has the potential to reduce labor costs by over \$300 million annually plus the savings which could be realized by the reduction in inputs to the NARF's plus the savings which could be realized by the reduction in the percentage of overbuy in procurement.

2. Conclusion. Statistical reliability analysis concepts and decision-logic are not general knowledge throughout the spectrum of Naval management today; this situation is incompatible with the proposed change to a SRA based system.

Recommendation. Expand the present workshop programs similar to the seminars conducted by Aero Data Inc. and embodied in Ref. 5. While the motivation of Naval managers is not questioned, the educational background must not be lacking in exposure to what is considered to be the state-of-the-art in managerial techniques. The diversity of education existing in middle and upper management levels of the U. S. Navy today does not always provide the necessary basis for this cognition. This academic effort will ensure the complete understanding of organizational goals and the policies to be followed in the achievement of those goals.

3. Conclusion. The decision logic of the MSG-II should be modified to eliminate some unnecessary steps. The decision tree shown in Figure 3 requires the analysis of each component failure mode and what maintenance action could be taken to restore the item's inherent reliability. The authors feel (and the authors of Ref. 2 concur) that it is of no benefit to list all possible maintenance actions for each failure mode when in most cases the component in question has no bearing on safety-of-flight or economics. If maintenance actions do not improve safety reliability and do not conserve resources, it should not be accomplished regardless of its effect on the reliability of that item.

Recommendation. Modify the decision logic depicted in Figure 3 to reflect the logic shown in Figure 5. The deviation from the original is incorporated to eliminate the aforementioned superfluosness. This is accomplished by simply first asking whether or not the component affects operational safety or economics. If the answer is yes, then possible maintenance actions which could restore the component's resistance to failure are listed. If the answer is no, then the component automatically becomes a "condition-monitored" item and no further action is necessary.

The benefit of incorporating this recommendation is, of course, to simplify the decision tree process and therefore allow its application to be completed in less time and with less confusion.

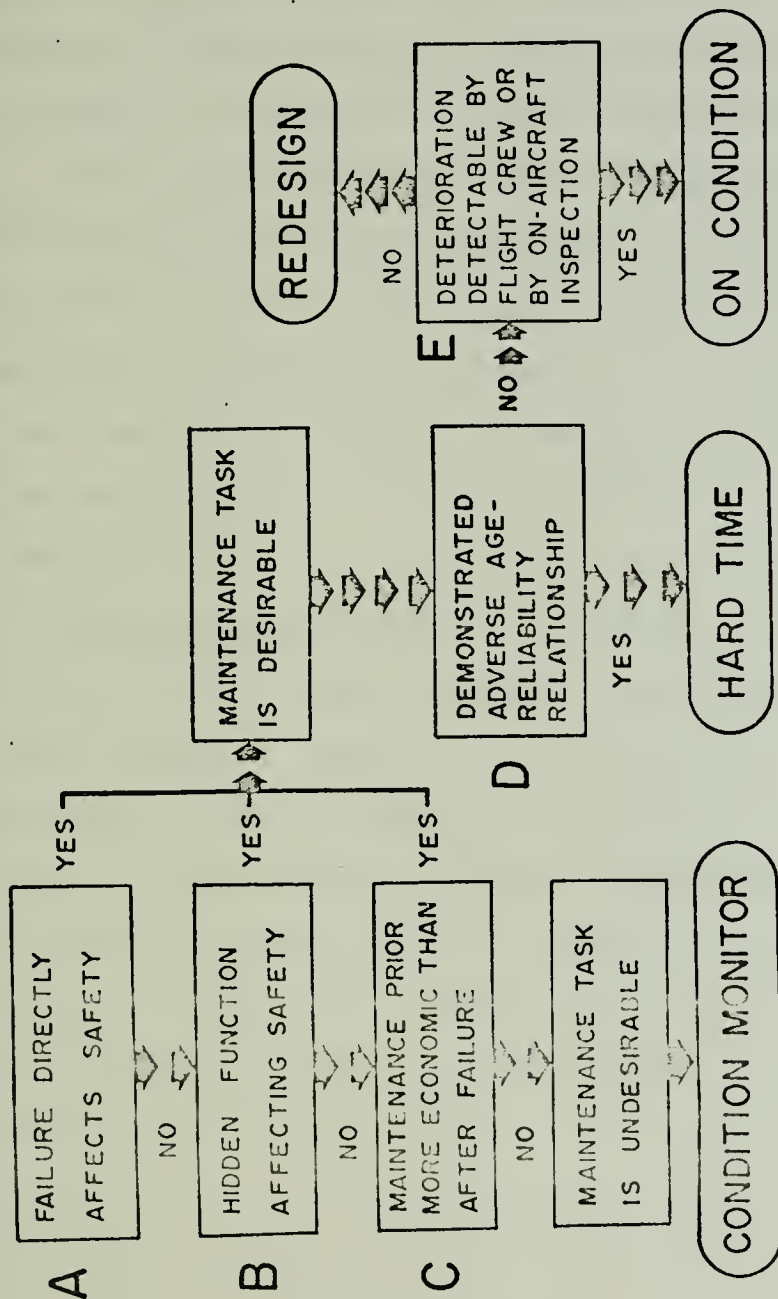


FIGURE 5. MAINTENANCE TASK DECISION LOGIC

THIS DECISION DIAGRAM IS AN ABRIDGEMENT OF THE MSG-II DECISION LOGIC. IT REPRESENTS AN ATTEMPT TO SIMPLIFY THE PROCESS OF DETERMINING INTO WHICH MAINTENANCE CATEGORY AN AIRCRAFT COMPONENT WILL BE PLACED. MAINTENANCE MUST BE COMPLETELY JUSTIFIED ON THE GROUNDS OF SAFE RELIABILITY OR ECONOMY. REDESIGN CAN ALSO MEAN INCORPORATION OF A WARNING DEVICE OR REDUNDANT SYSTEM. SOURCE: REF. 2, P.39.

4. Conclusion. The necessity for improved resource allocation in the U. S. Navy has reached proportions which demand immediate action at all strata of Naval management. Reduced manning levels of the operating forces and austere funding for supply support threaten the Navy's capability to perform its numerous military commitments.

Due to the time requirements for gathering all of the pertinent data, full implementation of MSG-II concepts or any similar decision logic will require several years. Statistical reliability analysis does not have to be considered to be a zero-sum concept. It may be incorporated in logical steps over a period of time, as suggested in the following recommendation.

Recommendation. Apply the decision logic of Figure 5 to all presently extant scheduled maintenance requirements. If the answers to questions A, B and C are no, then any maintenance task is undesirable. If the answer to questions A, B or C is yes and the answer to question D is no, then the component is placed in the on-condition category or requires redesign consideration. The application of the revised MSG-II decision logic can be successful up to this point with minimal delay. There remains only one additional possible outcome which has not been satisfied. That eventuality occurs when the answer to question A, B or C is yes and the answer to question D is yes. The Navy does not have, at the present time, the statistical data base required to compute the hard

time removal intervals. However, the Navy does have existing hard time removal intervals which could continue to be used until the empirical data is accumulated and more accurate intervals computed.

This partial implementation of a statistical reliability based system will provide immediate improvements in the allocation of financial and labor resources by eliminating the undesirable expenditure of man-hours and the unnecessary use of consumables.

The statistics generated by the airlines (Ref. 6 and Ref. 7) and Patrol Squadron 40 (Refs. 10, 11, 12, 13) indicate that components which require hard time removal total less than 10 percent of the items analyzed. If this trend holds in the application to all Naval aircraft, a man-hour savings of 20 to 25 percent is more than reasonable to expect due to the increasing number of items moving from the on-condition and hard time categories to the condition-monitored category.

APPENDIX A

GLOSSARY

ACE. Aircraft Condition Inspection.

Aircraft Utilization. The average daily flying hours for one aircraft. It is computed by dividing the total flying hours accumulated by a group of identical aircraft in a reporting period by the number of in-service aircraft days during the same period. Utilization may also be expressed in flying hours per month or per year.

Availability. Applies to flyable aircraft in such material condition to be safely capable of normal flight operations.

Calibration. The application of a known and accurately measured input to insure that an item will produce specifically known output which is accurately measured or indicated.

Cannibalization. The maintenance convenient removal of serviceable parts from one aircraft or equipment for installation in another aircraft or equipment.

Component. Any part, combination of parts, subassemblies, or units which perform a distinct function necessary to the operation of an aircraft system.

Concept, maintenance. Management ideas and principles which are studied and then developed into a specific, logical plan for application through a particular maintenance program.

Condition Monitoring. Non-preventive maintenance process wherein failures are allowed to occur and which relies upon analysis of operating data on the whole population of specified items to indicate whether some allocation of technical resources is required. Failure modes of condition monitored items do not have a direct adverse effect on operating safety. (Also known as "fly to failure.")

Consumable. An item which, after use, cannot be economically restored to a serviceable condition and loses its identity as a spare part.

Downtime. The time that an aircraft is on the ground out of service.

Experienced Judgement. Judgement based upon professional experience. It normally includes a very subjective conservatism such as, "This type of equipment has operated successfully for X number of hours in the past, but to be on the safe side, let's start with X-Y hours for the maintenance interval in this new item."

Hard Time. A primary maintenance process referring to the scheduled removal or maintenance of an item when the probability of failure begins to increase rapidly. The item must adversely affect safety or be more economical to replace prior to failure, and have an adverse age-reliability relationship.

Hidden Function. A component has a hidden function if
1. it is normally active but there is no indication to the flight crew when it fails, or 2. the component is normally inactive and there is no prior indication to the flight crew that the function will not perform when called upon. All components with hidden functions require some form of scheduled maintenance to be performed on them.

IMP. Improved Maintenance Program.

Infant Mortality. That high rate of failure which is significant during the early age of a component or assembly.

Inherent Level of Reliability and Safety. The highest level of reliability and safety which is built into, and can be expected from, a unit, system or aircraft and is therefore inherent in its design. Modification or redesign is required to achieve a higher level.

IRAN. Inspect And Repair as Necessary.

Item. Any level of hardware assembly, e. g., part, component, subsystem, system.

Item, Maintenance Significant. Maintenance items judged to be the most important from a safety, reliability or economic standpoint.

Item, Structurally Significant. Areas of primary structure judged to be the most important from a fatigue, corrosion vulnerability, or failure effects standpoint.

Maintenance. Those actions required to restore or preserve an item in serviceable condition, including servicing, repair, modification, overhaul, inspection, and determination of condition.

Maintenance, On-condition. A primary maintenance process having regular, repetitive inspections or tests to determine the condition of units, systems, or portions of structure with regard to serviceability. The item must affect safety and be responsive to maintenance.

Maintenance, Scheduled. That preventive or routine maintenance performed at defined intervals to retain an item in a serviceable condition by systematic inspection, detection, replacement of wearout items, adjustment, calibration, or cleaning.

Maintenance, Unscheduled. That corrective or nonroutine maintenance performed to restore an item to satisfactory operating condition by correcting a known or suspected malfunction or defect.

Malfunction. The occurrence of a condition whereby the operation of an item is outside satisfactory specified limits.

Man-hours per Flight Hour. A performance figure calculated by dividing the direct man-hours expended to maintain a particular group of aircraft during a given period by the group's flying hours during that period.

NAMP. Naval Aviation Maintenance Program.

NARF. Naval Aircraft Rework Facility.

NORM. Not Operationally Ready, Maintenance. That aircraft status indicating unavailability for mission performance pending accomplishment of maintenance.

Overhaul. The restoration of an item in accordance with instructions in the relevant manual; usually a major disassembly of the item.

Overmaintain. The performance of maintenance actions which during a period of relatively low probability of failure, is not justified economically; usually too far in advance of time-based deterioration.

Part. One piece, or two or more pieces joined together which are not normally subject to disassembly without destruction of the designed use.

PDLM. Periodic Depot Level Maintenance.

Plan, Maintenance. A document ~~or set of~~ documents which specifies the maintenance required to assure continued satisfactory performance of an item or the safety of an aircraft.

Program, Continuous Maintenance. A complete maintenance program which will assure continuous availability of an aircraft. The total maintenance effort is apportioned to each of the various and more frequent types of maintenance. A complete overhaul is not part of a continuous maintenance plan.

Program, Maintenance. A program which defines a logical sequence of maintenance actions to be performed as events or pieces of the whole which, when performed collectively, result in achievement of desired maintenance standards.

Rate, Failure. That performance figure which is the quotient of number of failures divided by total hours accumulated during the same period. Failure rate is the reciprocal of the mean time between failures.

Reduction in Failure Resistance. The deterioration of inherent levels of reliability. As failure resistance reduces, failures increase; resulting in lower reliability. If reduction in failure resistance can be detected, maintenance can be performed prior to the point where reliability is adversely affected.

Redundancy. The existence of more than one means to accomplish a given function. The alternative means need not necessarily be identical. Redundancy may be active or standby. Active redundancy connotes simultaneity whereas standby redundancy indicates that the backup system is inoperative until failure of the primary system.

Reliability. The probability that a component will perform a required function without failure under specified conditions for a specified period of time.

Reliability Analysis. The statistical assessment of the probabilities of satisfactory performance of an item over a specified operating span.

Removal. The deliberate detachment of a component from an aircraft. Removals are classified into one of three categories: scheduled, unscheduled, and maintenance convenient. A scheduled removal may be considered unjustified if no defect or failure is found.

Removal, Unscheduled. A removal of a component brought about as a result of a known or suspected malfunction or defect.

Removal Rate. The number of removals of an item expressed in terms of a base period, such as number per 1000 aircraft flight hours.

Repair. The restoration of an item to a serviceable condition.

Repairable Part. An item which is repaired after usage rather than discarded because it is more economical to do so.

Resources, Maintenance. Facilities, ground support equipment, manpower, spares, consumables, and funds available to maintain and support an aircraft in its operational environment.

Spares. The individual items held for the purpose of providing replacements for those removed from an aircraft for overhaul, repair, or modification.

System. A combination of interrelated items arranged to perform a specific function.

Time, Turnaround. That time needed to repair, service, or inspect an item or aircraft for return to operational service.

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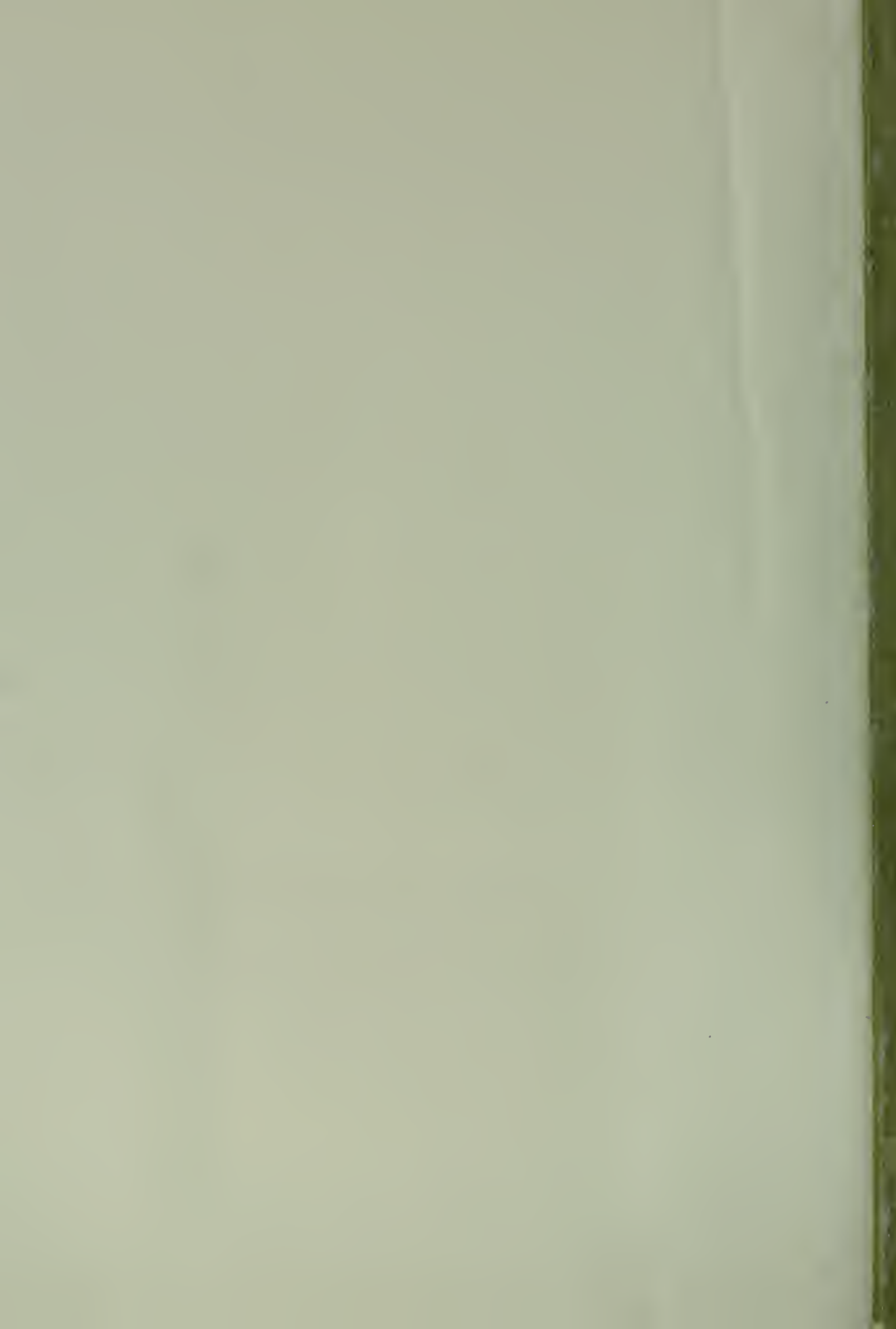
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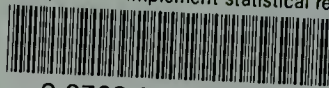
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